Re-entrant Coulomb Drag Between Vertically-Coupled Quantum Wires

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Motivation

Goal : Study electron interactions between 1 dimensional systems coupled at the nanoscale

- Address the wires multiple 1D subbands regime
- Study one-dimensional electron-hole asymmetry
- Ultimately investigate Luttinger liquid theory

Tool : Coulomb Drag measurement

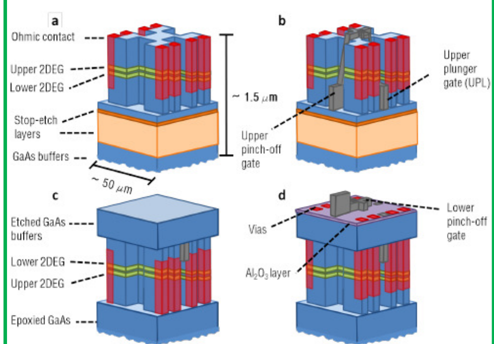
- Direct probe of electron-electron interactions

How : Independent and vertically-coupled quantum wires

Device fabrication

Start with double quantum well GaAs/AlGaAs heterostructure with double stop-etch layer.

- 18 nm wide quantum wires.
- Density of 1.1 (1.4) × 10^{11} cm^{-2} for the lower (upper) layer and combined mobility of 4.0 × 10^5 $cm^2 / V \cdot s$.



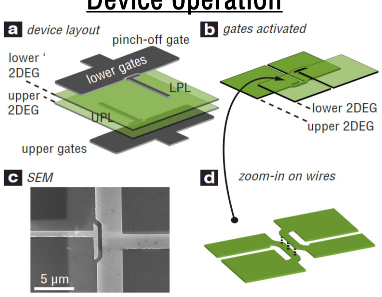
a) Defining the mesa, and depositing and annealing ohmic contacts.

b) Defining the upper gates, using a combination of both photo and e-beam lithography,.

c) Performing an Epoxy-Bond-And-Stop-Etch (EBASE) technique [1] , which consists of gluing bare GaAs on top of the device and flipping it, then etching the original substrate until the lower 2DEG is ~ 150 nm away from the surface.

d) Depositing an insulating Al_2O_3 layer and defining the lower gates, which are now on top of the device.

Device operation



Advantages of design :

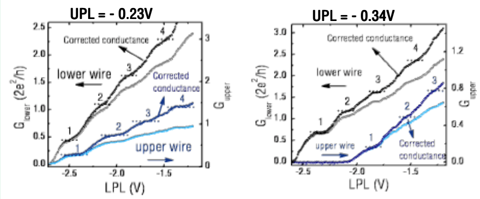
- Independent ohmic contacts, with suitable bias on gates → Probe both wires independently
- Independent control of 1D subbands occupancy in each wire → Easy to study multiple and single 1D subbands regimes
- Hard MBE-defined barrier between the wires →
  - Fixed interwire separation
  - Interwire separation in the 10's nm range possible
  - Regime where Coulomb drag dominates
  - Stronger drag signal
  - Stronger interwire many-body interactions

Current wire properties :

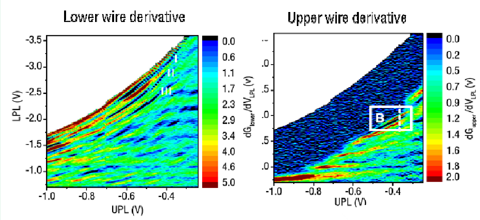
- 4.2 μm long wires
- Barrier of 15 nm between both wires
- Effective center-to-center interwire separation ≤ 41 nm

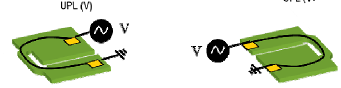
Wires characterization

- The plunger gates are coupled to both wires → Sweeping a single gate affects both wires
- Non-ballistic wires are observed → $G < 2e^2/h \times N$; N = number of 1D subbands
- After subtracting series resistance, approximately even spacing between steps is observed
- Consistent with non-ballistic 1D subbands [2]
- Similar (UPL = -0.23V) and different (UPL = -0.34V) subband occupancy can be achieved.



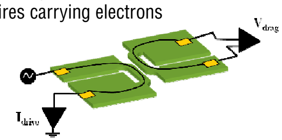
- A complete mapping of the wires conductance can be performed as a function of UPL (upper plunger) and LPL (lower plunger)
- The wire's features are more apparent in the derivative → 1D subbands appear as black and blue stripes
- 1D subbands can be tracked over the whole gate voltage range.





Coulomb drag basics

- Coulomb drag is a direct probe of electron-electron interactions.
- Send a current I_{drive} in one wire
- Measure the resulting voltage drop V_{drag} in the other wire → No current flow allowed in the drag wire
- Measured quantity is the transresistance → $R_D = \frac{-V_d}{I}$
- Theory predicts a positive drag between two one dimensional wires carrying electrons



Acknowledgements

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McGill

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Main results

3 regimes are observed in the Coulomb drag measurement

1- Positive drag : Peaks are observe as 1D subbands open . in either wire (dotted gray lines)

→ Previously observed by Debray *et. al.* [3] and predicted from electron-hole asymmetry [4].

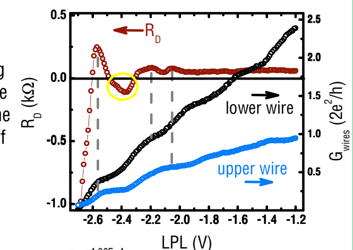
2- Low-density negative Coulomb drag : occurs at highly negative LPL values

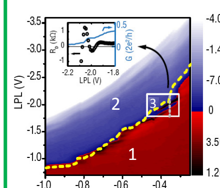
→
- Previously observed by Yamamoto *et. al.* *[2]* in similar conditions but in the presence of a magnetic field.
- Was attributed to Wigner crystallization

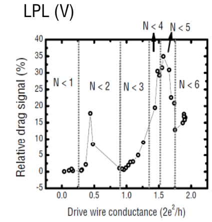
3 – High-density re-entrant negative Coulomb drag (yellow circle)

→
- Never observed previously
- Is inconsistent with Wigner crystallization
- Might be caused by a non-monotonic in the wires transmission probability coupled with electron-hole asymmetry or by a local hole-like dispersion relation in the quantum wires band structure.

The three drag regimes can be tracked over the whole range of gate voltage.







The maximal amplitude of the drag signal can reach up to 35 % of the drive signal.

Coulomb drag tests

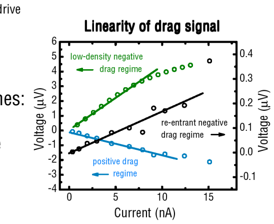
Several tests were performed to insure that the signal observed was truly Coulomb drag.

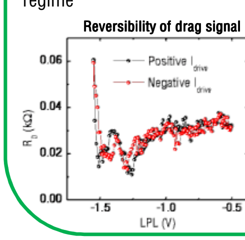
1- V_{drag} is linear with I_{drive} for small enough excitation

→ $eV_{drive} \lesssim 3$ K

True for all three regimes:

- positive regime
- high-density negative regime
- low-density negative regime





2- R_{drag} is independent of I_{drive} direction

3 – R_{drag} is independent of frequency

4 – No DC signal is observed in the drag wire when an AC I_{drive} is sent through the drive wire.

Conclusion

Summary :

- Fabricated the first vertically-coupled quantum wires suitable for Coulomb drag measurements
- Measured Coulomb drag and observed both positive and negative regimes
- Observed new re-entrant negative drag which is inconsistent with Wigner crystallization and ill-understood at the moment

Future directions : Study temperature dependence of Coulomb drag

- Understand origin of negative Coulomb drag
- Study Luttinger liquid physics